



Design and experimental investigations on a small scale traveling wave thermoacoustic engine

M. Chen, Y.L. Ju *

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, PR China

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ABSTRACT

A small scale traveling wave or Stirling thermoacoustic engine with a resonator of only 1 m length was designed, constructed and tested by using nitrogen as working gas. The small heat engine achieved a steady working frequency of 45 Hz. The pressure ratio reached 1.189, with an average charge pressure of 0.53 MPa and a heating power of 1.14 kW. The temperature and the pressure characteristics during the onset and damping processes were also observed and discussed. The experimental results demonstrated that the small engine possessed the potential to drive a Stirling-type pulse tube cryocooler.

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1. Introduction

Based on thermoacoustic effect [1–3], the thermoacoustic heat engine is regarded as a new type of promising and environmentally-friendly machine because it has no mechanical moving component and can run with low quality heat sources like industrial waste heat and solar energy, which makes it competitive to drive refrigerators, cryocoolers to liquefy the natural gas as an example and drive generators in some remote districts where electric power is short but solar energy is rich. Of the two types of thermoacoustic heat engines, traveling wave thermoacoustic engines generally outperform standing wave based ones, due to the ideally reversible heat transfer in the regenerators. Therefore, more attention is being focused on the traveling wave thermoacoustic engines in recent years and wide application is greatly expected. Many traveling wave thermoacoustic engines have been built and studied all over the world [4–8]. Backhaus and Swift [4] firstly developed such an engine that could achieve a high thermal efficiency of 0.30, which formed the milestone in the history of traveling wave thermoacoustic engines. Ercang et al. [6] modified an energy-focused traveling wave thermoacoustic engine with an entirely tapered resonator, which could obtain a very high pressure ratio of 1.40. However, the above mentioned engines are very large with resonators usually over 5 m despite the relatively high pressure ratio and low frequency, which restricts their application in some particular fields, such as space exploration. Small scale engines have the superiority over large ones in those fields that do not permit large occupation

of space. Several small scale traveling wave thermoacoustic engines [9,10] were reported. Gang et al. [10] designed the smallest traveling wave thermoacoustic engine with length of 0.65 m, height of 0.22 m, frequency of 282 Hz and maximal pressure ratio of 1.116. For a pulse tube cryocooler, the driver's pressure ratio is normally over 1.1 and supposed to be higher to obtain a good cooling performance. High pressure ratio and low frequency is what the researchers in thermoacoustics are endeavoring to achieve. In this paper, a small scale traveling wave thermoacoustic heat engine with the potential to drive a pulse tube cryocooler is presented.

2. Experimental setup

Fig. 1 shows the schematic diagram and the photo of the prototype of the small traveling wave thermoacoustic engine, designed and constructed in SJTU. It mainly consists of two parts, a loop and a resonator. Beginning at the resonator junction and anti-clockwise around the loop are the second ambient heat exchanger, the buffer tube, the heater, the regenerator, the main ambient heat exchanger, the compliance and the inertance tube concluding a corrugated pipe. A detailed description of the main parts will be given in the following.

2.1. Heater

Fig. 2 shows the schematic diagram and photo of the heater which consists of an inner copper block with many regular comb slots through which the gas passes and an outside round stainless steel vessel. It has six holes that can hold six cartridge heaters from

* Corresponding author. Tel./fax: +86 21 34206532.

E-mail address: yju@sjtu.edu.cn (Y.L. Ju).

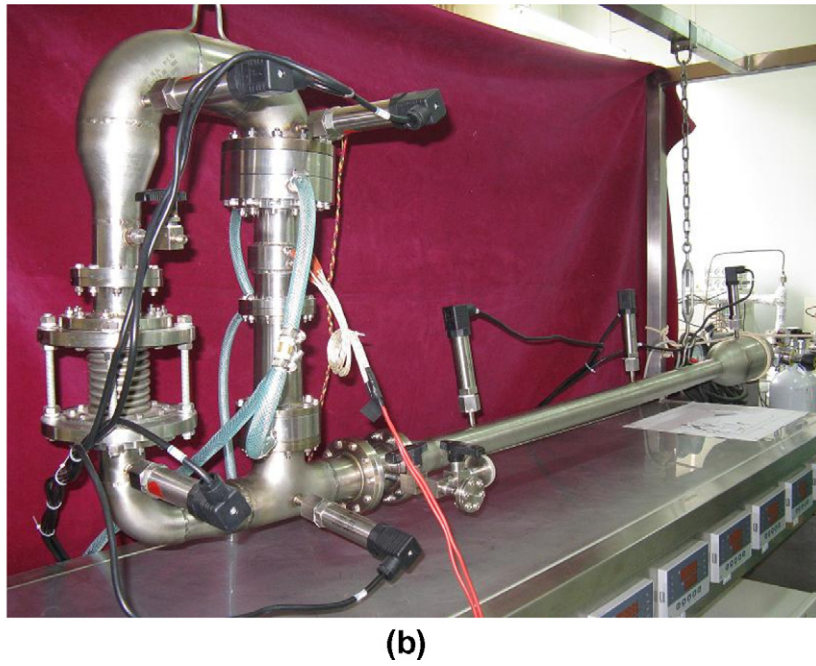
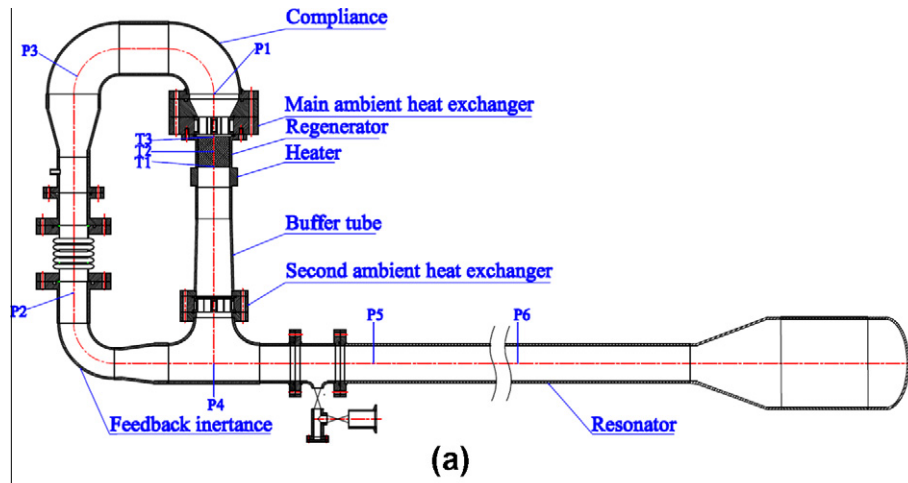


Fig. 1. The schematic diagram (a) and photo (b) of the small traveling wave thermoacoustic engine.

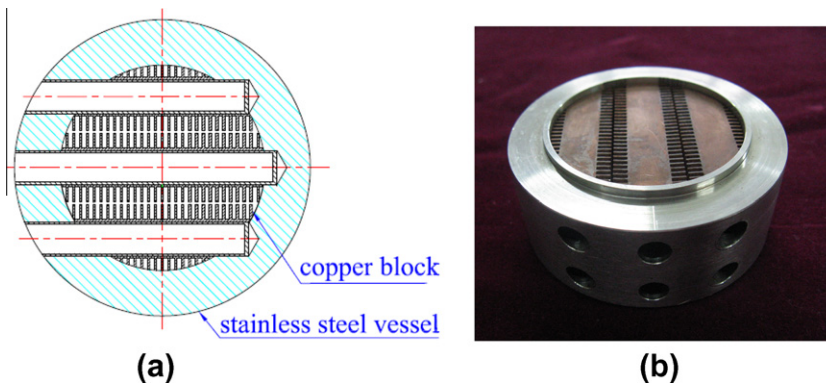


Fig. 2. The schematic diagram (a) and photo (b) of the heater.

Watlow through which up to 1.2 kW heating power can be supplied.

2.2. Regenerator

Above the hot heat exchanger is the regenerator, made from a 39 mm tall stack of 100-mesh stainless-steel screens with a diameter of 44 mm placed in a thin-wall tube. The whole length of the regenerator is 43 mm with an e-like support on each side to hold the screen. The diameter of the screen wire is 0.1 mm. The calculated volume porosity and the hydraulic radius are 0.67, and 50 μm respectively. Fig. 3 is the photo of the regenerator. The regenerator and the heat exchangers on each side constitute the core of the engine where the thermoacoustic effect occurs.

2.3. Ambient heat exchangers

The main and the second ambient heat exchangers have the similar structures as shown in Fig. 4. The working gas passes through the inner slots while the water flows through the annular channel formed by the copper block and the stainless steel vessel and the straight channel in the middle to carry away the heat rejected by the engine during operation.

2.4. Other acoustic ducts in the loop

The compliance actually consists of two elbows and a short straight tube with an inside diameter of 70 mm. The inertance tube containing a fill line consists of a cone connected to the tee, an elbow, a straight tube with a corrugated pipe and another cone connected to the compliance as shown in Fig. 1. Between the hot heat exchanger and the second ambient heat exchanger is the tapered buffer tube acting like a pulse tube in a Stirling-type pulse tube cryocooler [11].

2.5. Resonator

The resonator junction with the loop is a stainless steel tee. Three types of resonators are prepared for experimental tests. A straight tube with the length of only 1 m and the inside diameter of 39 mm is firstly connected to the tee with a cone as the main resonator. Another cone is used to join the main resonator and a very short straight tube terminated in an ellipsoidal cap.

3. Measurement system

Three thermocouples are used to measure the temperature profile of the regenerator. Among them, one type-T thermocouple is placed close to the cold end of the regenerator. The other two type-K thermocouples are respectively put in the middle axially

and at the hot end centre through a tiny hole drilled into the regenerator as shown in Fig. 3. The leads are taken outside from a tie-in with seal equipment to Keithley data acquisition system. Via the three thermocouples, the accurate temperature gradient needed for oscillation and the evaluation of the Gedeon streaming can be obtained.

Six dynamic pressure sensors are used to measure the pressure signals. The electric signals generated by the pressure sensors are transferred to a NI acquisition board PCI 6143. The acquisition procedure is written with the virtual instrument Labview 8.0.

4. Experimental results and discussions

The thermoacoustic phenomenon starts when the temperature difference between the hot and cold side of a regenerator or a stack surpasses a critical value and an oscillation is generated. Fig. 5 and Fig. 6 show the temperature and the pressure characteristics of the small traveling wave thermoacoustic engine during the onset process, respectively. Using nitrogen gas with an average charge pressure of 0.35 MPa, the oscillation occurred when the hot and the cold temperature reached 554 $^{\circ}\text{C}$, 100 $^{\circ}\text{C}$, respectively, i.e., the onset temperature difference across the regenerator was 454 $^{\circ}\text{C}$. After the oscillation took place, the hot temperature dropped immediately as the heat converted to acoustic work instantaneously. The cold temperature and the middle temperature both had a fairly quick but small rise due to the gas rushed from the hot end toward the cold end just at the moment of the oscillation and then dropped immediately, similar to the hot temperature. Owing to the balance of energy conversion under a given operating condition, the three temperatures eventually became stable at 311.5 $^{\circ}\text{C}$, 165 $^{\circ}\text{C}$ and 42.5 $^{\circ}\text{C}$, respectively.

The pressure in the engine fluctuated slightly before the strong oscillation started because of the heat supply. It can be found in Fig. 6, the pressure changed very fast from initially almost static status to obviously oscillating status in just 2 s during the onset process. The onset heating temperature is plotted as a function of the average charge pressure, as shown in Fig. 7. The temperatures on the cold end of the regenerator under different charge pressures were all slightly above 100 $^{\circ}\text{C}$ when the oscillation began. As mentioned above, three thermocouples were installed through the hole drilled into the regenerator. Therefore, heat could be transported to the cold end via the metal materials of the thermocouples, which caused the temperature on the cold end of the regenerator to be higher. It is found during the experiments that the temperature on the cold end of the regenerator is of more importance to build the essential gradient across the regenerator and thus lower the onset heating temperature. Some measures will be considered to lower the temperature on the cold end. The onset heating temperature reached a minimum with an average charge pressure of 0.35 MPa. When the average charge pressure exceeded 0.35 MPa,

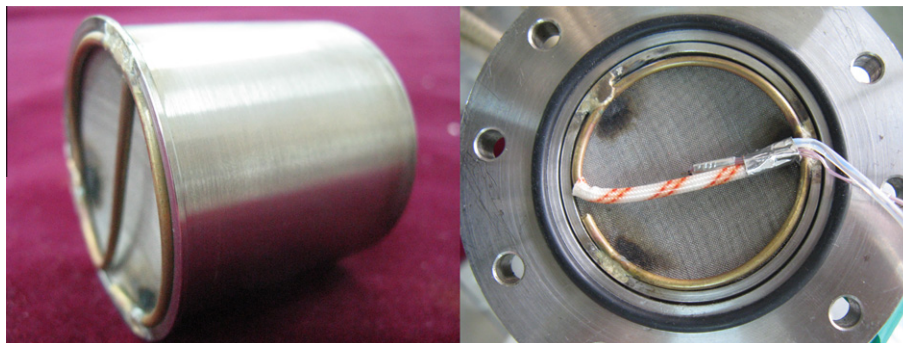


Fig. 3. The photo of the regenerator.

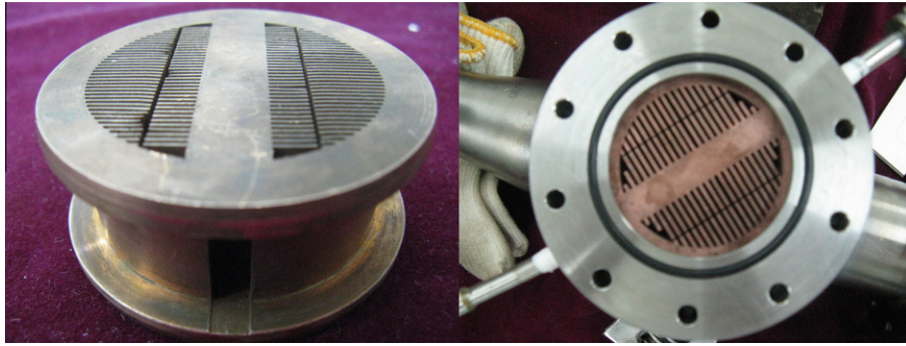


Fig. 4. The photo of the ambient heat exchangers.

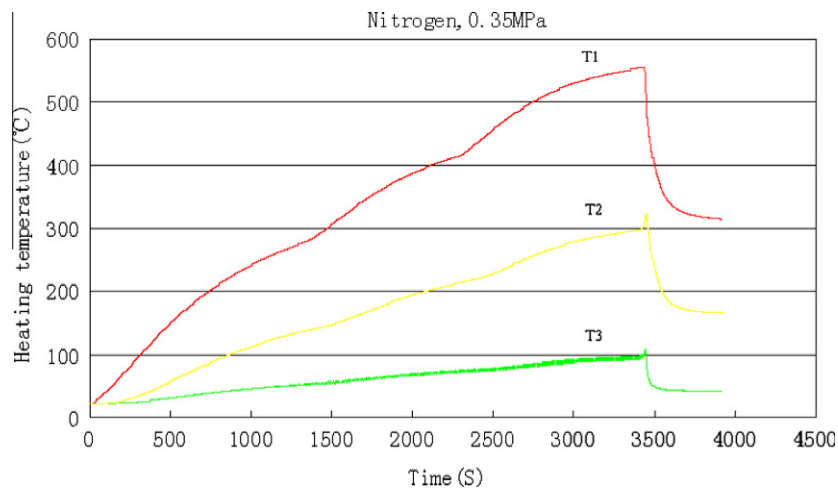


Fig. 5. The temperature characteristics during the onset process.

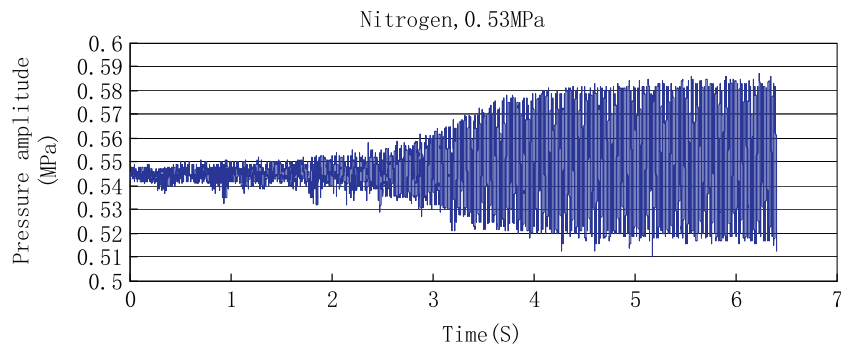


Fig. 6. The pressure characteristics during the onset process.

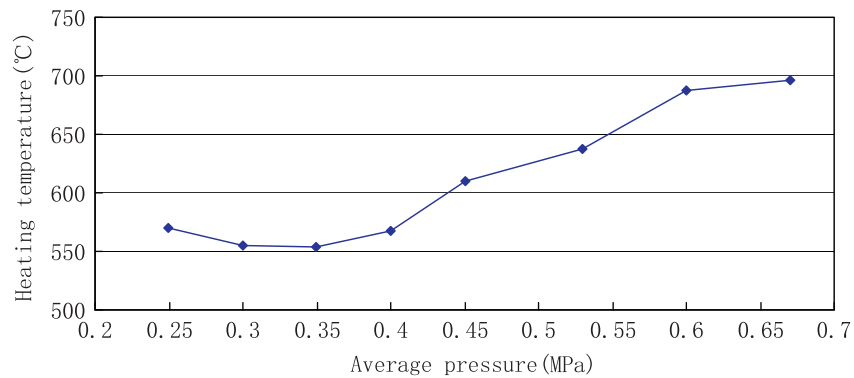


Fig. 7. The pressure characteristics during the damping process.

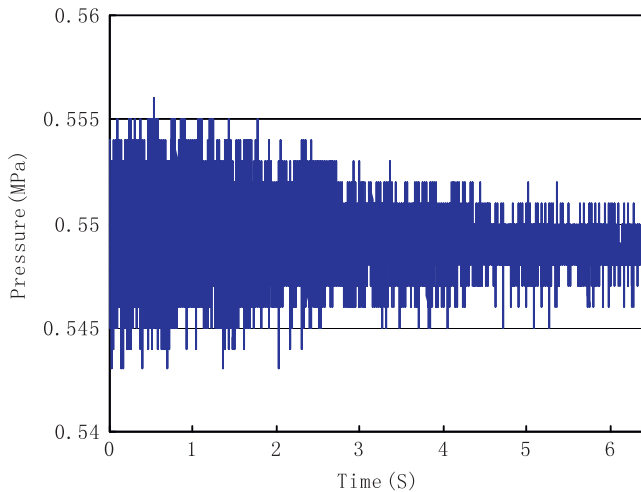


Fig. 8. The onset heating temperature vs. the average charge pressure.

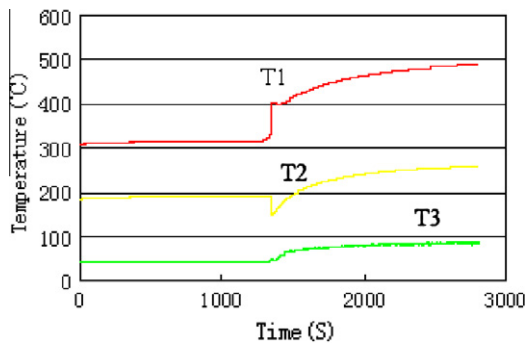


Fig. 9. The temperature characteristics during the damping process.

the onset heating temperature obviously increased. This demonstrated that appropriate charge pressure contributed to have a relatively low onset heating temperature.

The heating power is the driving source of a thermoacoustic heat engine. When the heating power was reduced below the power needed for maintaining the oscillation, the oscillation amplitude got smaller and smaller and finally disappeared, i.e., the engine became quiet again. If the power was suddenly switched off, the oscillation disappeared right away. Fig. 8 and Fig. 9 plot the pressure amplitude and temperature variations during the damping process under the former condition. The remaining heat could not be converted to acoustic power after the

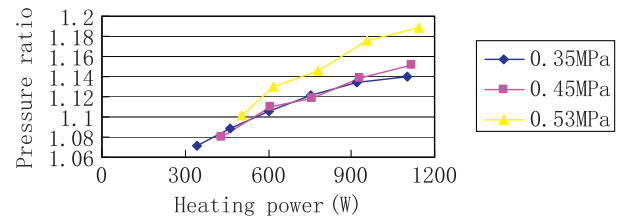


Fig. 11. The pressure ratio vs. the heating power.

oscillation in the engine disappeared, so the temperature of the hot end increased. Both the temperatures in the middle and at the cold end had a quick small drop and then rose up because of the heat conducted from the hot end.

The pressure ratio as a function of the average charge pressure is given in Fig. 10. Higher average pressure usually means higher energy density. However, it does not mean the higher pressure ratio for the ratio is determined by both the amplitude and the mean pressure. An inflexion came as the average pressure changed. The pressure ratio reached its maximal value of 1.189 with an average charge pressure of 0.53 MPa. Repeating the test under the same condition showed good repeatability. From the above discussion, it is seen that several aspects should be comprehensively taken into account to decide an appropriate charge pressure to achieve a generally good performance.

The pressure ratio as a function of the heating power under different average charge pressures is plotted in Fig. 11. Since more heating power means more powerful drive for the engine, it is apparent that the pressure ratio increases monotonously with the increase of the heating power.

The working frequencies of the engine are quite stable at 45 ± 0.5 Hz under different average charge pressures, with good compatibility with a common Stirling-type pulse tube cryocooler. This frequency value has a great deviation from the simulation value (118 Hz) with DELTAEC [12]. Maybe the numerical model needs improvement. If the whole resonator length together with half the length of the loop is taken as a quarter of the wave length, the estimated frequency (42 Hz) related with acoustic speed would be in better accordance with the experimental results. It means that this small traveling wave thermoacoustic heat engine is definitely not a traditional $\lambda/4$ system (65 Hz) whose frequency can be simply estimated mainly with the resonator length. Further study is planned to reveal the reason.

Fig. 12 shows the typical pressure waves at different points in the engine, using nitrogen gas with an average charge pressure of 0.45 MPa and a heating power of 930 W. P1 is located above the main ambient heat exchanger. P2 is placed near the entrance of the inertance tube at the lower left corner of the loop. P3 is

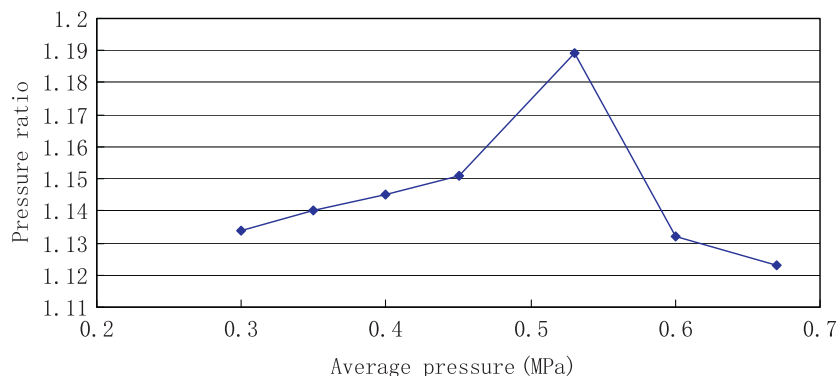


Fig. 10. The pressure ratio vs. the average charge pressure.

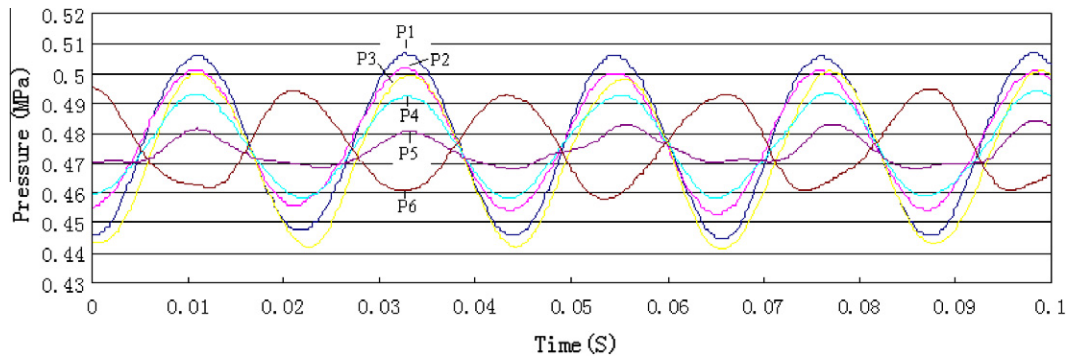


Fig. 12. Typical pressure waves at different points in the engine.

installed near the entrance of the compliance at the upper left corner of the loop. P4 is put near the tee. P5 is installed near the left end of the main resonator. P6 is placed in the middle of the main resonator. It can be seen that the pressures in the loop almost have the same phases and the wave shapes are almost stable. The engine has its maximal pressure amplitude above the main ambient heat exchanger where a combination with a Stirling-type pulse tube cryocooler can be implemented with an elastic membrane to transfer the acoustic power if nitrogen is used as working gas. Further experiments will be carried out with helium since it is a good alternative as working gas for common refrigerators and cryocoolers.

5. Conclusions

A small scale thermoacoustic engine based on traveling wave phasing with a resonator of only 1 m was designed and studied firstly with nitrogen gas. The experimental measurements demonstrated that the pressure ratio reached 1.189, with an average charge pressure of 0.53 MPa and a heating power of 1.14 kW. A quite steady working frequency around 45 Hz was achieved. The characteristics of the temperature and the pressure during the onset and damping processes were also observed and discussed to help understand how the acoustic oscillation was generated. The small engine deviated from a traditional $\lambda/4$ system while its general performance was satisfying in the range of small scale traveling wave thermoacoustic or Stirling thermoacoustic engines, which showed the engine had the potential to drive a pulse tube cryocooler. However, the heating temperature of the prototype engine was too high to use low quality heat source such as waste heat. Further experiments and improvements aimed to drive a Stirling-type pulse tube cryocooler will be conducted in near future.

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